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Will policies to promote renewable electricity generation be effective? Evidence from panel stationarity and unit root tests for 115 countries

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ABSTRACT

This study examines whether policies to promote renewable electricity generation are likely to be effective by applying panel unit root and stationarity tests to time series data on renewable electricity generation for 115 countries over the period 1980–2008. We find that for the panel as a whole, and almost three quarters of the individual countries, renewable electricity generation is characterized by a unit root. This result implies that policies to promote renewable electricity generation, such as renewable portfolio standards, which result in annual increases in renewable energy and, as such, which represent permanent positive shocks to the long-run growth path of renewable electricity generation, will be more effective in increasing renewable electricity generation than policies with a pre-specified time horizon.

Contents

1. Introduction

The world's demand for energy is expected to rise [1]. There is considerable concern about the potential for fossil fuels to continue to contribute the lion's share of energy in the future for two reasons. The first is that reserves of fossil fuels are expected to peak by 2030 and decline thereafter. The other is concern about the adverse environmental effects of burning fossil fuels [2]. At the same time, there have been setbacks to the development of nuclear energy, such as the Fukushima nuclear disaster in Japan in 2011, which has raised serious concerns about the safety of nuclear energy. Some see renewable energy as representing one answer to the world's energy needs [2–6]. The Kyoto Protocol on Climate Change was a catalyst for countries setting targets for increasing renewable energy in the energy mix. There are now 66 countries which have targets for renewable energy, specified in terms of a proportion of electricity generation, primary energy and/or final energy. These include 27 European Union countries, 29 states in the United States and nine Canadian provinces. For example, China has a target of making 15 per cent of primary energy come from renewable sources by 2020, while the European Union has the objective of making 20 per cent of its energy consumption come from renewable sources by 2020 [7]. To realize these objectives, several policies have been introduced to increase the share of renewable energy in the energy mix. Several of these policies are reviewed in depth in Refs. [5–6,8–13]. Policies to promote renewable energy include policies with a limited time horizon, such as one-off investment incentives or tax

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Table 1
Summary statistics for all countries: total renewable electricity generation (billion kW h) (1980–2008).

Country	Mean	Std. Dev.	Maximum	Minimum
Afghanistan	0.5738	0.1696	0.7700	0.2920
Albania	3.9287	0.8923	5.6690	2.7600
Algeria	0.2606	0.1504	0.6390	0.0530
Angola	1.1196	0.8086	3.8040	0.5300
Argentina	24.8028	7.3960	38.9553	12.9480
Australia	16.0919	1.9593	19.1407	12.3940
Austria	35.9800	4.9592	44.2749	26.2570
Bangladesh	0.8658	0.2730	1.4590	0.4500
Belgium	1.5439	1.1465	5.2263	0.5390
Bhutan	1.8262	1.7042	7.0630	0.0060
Bolivia	1.6202	0.4569	2.4529	1.1150
Brazil	248.9921	75.2406	387.7673	130.3588
Bulgaria	2.7444	0.6845	4.3148	1.4530
Burundi	0.0903	0.0440	0.2060	0.0020
Caledonia	0.3750	0.0728	0.5270	0.2540
Cambodia	0.0506	0.0136	0.0770	0.0280
Cameroon	2.8411	0.6997	4.1900	1.3500
Canada	324.6522	37.2437	390.3670	252.2330
Central African Republic	0.0813	0.0165	0.1300	0.0600
Chile	16.9153	6.6074	29.8561	7.4430
China	199.8443	128.2375	537.2981	57.6180
Colombia	29.3179	8.1745	43.6968	14.5330
Congo	5.9536	1.0666	8.0790	4.2280
Costa Rica	4.7932	2.1299	8.6535	2.0980
Cuba	0.8913	0.2316	1.2820	0.4372
Denmark	3.5278	3.8022	10.5151	0.0280
Dominica	0.0208	0.0079	0.0340	0.0090
Dominican Republic	0.9679	0.4188	1.9045	0.4160
Ecuador	5.5241	2.4996	11.5811	0.7830
Egypt	11.2347	2.5108	16.1440	7.8210
El Salvador	1.9623	0.5794	3.5608	1.2570
Equatorial Guinea	0.0029	0.0018	0.0070	0.0020
Ethiopia	1.5117	0.8496	3.3510	0.4730
Faroe Islands	0.0722	0.0176	0.1034	0.0490
Finland	17.7749	4.9402	27.4149	10.1150
France	67.1675	7.1229	80.4530	47.8050
Gabon	0.7268	0.1568	0.9426	0.2570
Germany	36.6771	20.2943	91.2524	20.3925
Ghana	5.1323	1.2679	6.7820	1.7990
Greece	3.7355	1.4372	7.5531	1.7520
Guatemala	2.4075	1.2696	5.1494	0.3940
Haiti	0.2727	0.0496	0.3680	0.1520
Honduras	1.6849	0.5327	2.4551	0.7720
Hungary	0.4816	0.6139	2.3562	0.1110
Iceland	6.0910	2.9295	16.1401	3.1030
India	74.0094	23.7001	132.4604	46.5400
Indonesia	10.1421	5.3080	19.3502	2.2340
Iran	7.9405	3.6618	18.2018	3.6250
Iraq	0.5707	0.0835	0.7030	0.3070
Ireland	1.1238	0.6500	3.4015	0.6730
Italy	46.8016	5.1470	59.3982	34.5586
Cote dIvoire (IvoryCoast)	1.4752	0.3656	1.9911	0.3690
Jamaica	0.2115	0.0499	0.3169	0.1240
Japan	100.0254	9.3125	115.9754	79.5804
Kenya	3.1015	0.9941	4.7272	1.1820
Korea, North	12.3593	1.6796	15.4440	10.0980
Korea, South	3.4475	1.0501	5.1200	1.5390
Laos	1.6988	1.1022	3.6798	0.4870
Lebanon	0.6627	0.2386	1.3490	0.2970
Luxembourg	0.1575	0.0598	0.3115	0.0990
Madagascar	0.4054	0.1579	0.7350	0.1460
Malawi	0.8334	0.3338	1.4850	0.3790
Malaysia	4.8217	1.7419	7.4450	1.2900
Mali	0.1960	0.0553	0.2750	0.0820
Mauritania	0.0333	0.0101	0.0600	0.0180
Mauritius	0.0935	0.0274	0.1470	0.0300
Mexico	30.2707	6.4223	46.5133	17.6000
Morocco	1.0590	0.4582	2.0620	0.3620
Mozambique	5.2677	5.9130	15.9020	0.0240
Burma (Myanmar)	1.6362	0.8253	3.9880	0.7880
Nepal	1.2186	0.8900	3.0420	0.1760
Netherlands	3.1456	3.0536	10.6355	0.0160
Nicaragua	0.6606	0.1829	1.1565	0.3500
Nigeria	5.0344	1.7684	8.1520	1.8560
Norway	112.6786	14.0375	139.4993	82.7170

Table 1 (*continued*)

Country	Mean	Std. Dev.	Maximum	Minimum
New Zealand	25.3315	2.8921	30.0497	19.5724
Pakistan	19.2300	6.3478	31.6330	8.6270
Panama	2.4944	0.8342	3.9511	0.9950
Paraguay	32.1471	20.0037	54.9090	0.6750
Peru	13.1604	3.9876	19.8633	7.1150
Philippines	12.8865	4.3151	19.8333	5.4500
Papua New Guinea	0.6386	0.2456	0.9340	0.3010
Poland	2.7001	1.1475	6.4734	1.6470
Portugal	10.9517	3.3888	17.7120	5.2290
Puerto Rico	0.1480	0.0525	0.2720	0.0674
Reunion	0.5073	0.0771	0.6510	0.3020
Romania	14.2028	2.7636	20.0120	9.9340
Rwanda	0.1269	0.0438	0.1710	0.0300
Saint Vincent/Grenadines	0.0229	0.0050	0.0360	0.0130
Samoa	0.0304	0.0159	0.0620	0.0070
Sao Tome and Principe	0.0076	0.0014	0.0100	0.0040
South Africa	1.4800	0.7912	3.1653	0.1460
Spain	34.7056	11.5488	60.4336	19.4664
Sri Lanka	2.9934	0.8707	4.4070	1.2040
Sudan	1.0372	0.2193	1.4480	0.4950
Suriname	0.9797	0.3034	1.4630	0.3230
Swaziland	0.1711	0.0411	0.2170	0.0650
Sweden	69.8566	8.1213	82.5489	53.4424
Switzerland	34.8842	3.1821	42.3364	29.5776
Syria	2.9446	0.4451	4.2050	2.4850
Taiwan	5.6420	1.2857	8.3008	2.9050
Tanzania	1.6783	0.5536	2.6930	0.9870
Thailand	6.1414	2.8032	12.0175	1.2600
Togo	0.1068	0.0603	0.2550	0.0190
Trinidad and Tobago	0.0211	0.0066	0.0310	0.0076
Tunisia	0.0801	0.0469	0.1950	0.0230
Turkey	27.6812	11.2953	45.8654	11.1300
Uganda	1.0604	0.4453	1.8880	0.5130
United Kingdom	9.1092	5.4712	22.2871	3.9210
Uruguay	6.2927	1.9532	9.4760	2.2590
United States	347.3696	48.8405	437.2481	238.0851
Venezuela	47.1537	21.4803	86.7050	14.4380
Vietnam	9.8969	7.7139	25.7260	1.1880
Zambia	8.4572	0.9962	9.9300	6.7020
Zimbabwe	3.3550	1.0940	5.7760	1.6280

credits and policies of a more permanent nature such as renewable portfolio standards, which call for annual increases in the share of renewable energy [7,14].

There is a growing literature which examines the order of integration of energy consumption and production [15]. This literature has applied a range of univariate and panel unit root and stationarity tests, with and without structural breaks, to aggregate energy consumption/production plus various types of disaggregated energy. The findings from a study such as this on the order of integration of energy variables speaks directly to the efficacy of attempts to increase the share of renewable energy in the world's energy mix. Policies such as renewable portfolio standards represent an attempt to generate a permanent positive shock to renewable energy. If the production of renewable energy is non-stationary, a shock to the long-run growth path of renewable energy will have permanent effects and policies, such as these, which result in continuing annual shocks, will be effective. However, if renewable energy is stationary, production of renewable energy will return to its long-run growth path and policies to promote renewable energy, such as tax credits, which have predetermined time horizons, will be temporarily effective in stimulating production.

Within the literature on the order of integration of energy variables, few studies have examined the integration properties of renewable energy consumption or production and those which have focus on the United States. It is important to examine the unit root properties of renewable energy in countries other than the United States. Global warming has been shown to be a significant determinant of renewable production in the G7 [16] and in developing countries [17–22], not just the United States. The potential for renewable energy production [23] and the effectiveness of policies [8,11–13,24] differ across countries. Another aspect of the existing literature is that there are no studies that consider renewable electricity generation, despite targets often being specified in terms of the share of renewable sources in electricity generation. For example, in 2009 Australia announced that by 2020, 20 per cent of electricity supply should come from renewable sources, while in the United States, it has been proposed that by 2035, 80 per cent of electricity should come from clean energy sources, with renewable energy sources having an important part to play [25].

The purpose of this study is to examine the integration properties of renewable electricity production for 115 countries using panel stationarity and unit root tests with, and without, structural breaks. The use of a large number of countries has the advantage that it is possible to use both a panel and allow for structural breaks, which was recommended as providing the most reliable evidence on the order of integration of energy variables by Smyth [15]. Specifically, in addition to a series of first generation panel unit root tests [26–28], we employ the Carrion-i-Silvestre et al. [29] panel stationarity test, which allows for multiple structural breaks. The Carrion-i-Silvestre et al. [29] test has not been employed very often in the literature on the unit root properties of energy variables (exceptions are [30,31]). It has

the advantage over other panel tests with structural breaks, such as the panel Lagrange Multiplier test, that in addition to providing information on the order of integration for the panel as a whole, one can ascertain the order of integration for individual countries. The test provides for multiple structural breaks, which are allowed to vary across individual countries.

2. Review of existing studies

Beginning with Narayan and Smyth [32] a sizeable literature has developed which examines the unit root properties of energy consumption and production. Here, we provide a brief overview of this literature. For a more detailed review, the reader is referred to Ref. [15]. One set of studies has applied univariate unit root tests without structural breaks to aggregate energy consumption for a large number of countries [32,33]. These studies have found that energy consumption is stationary for about one-third of countries studied. A problem with unit root tests without structural breaks is that failure to accommodate a structural break potentially reduces the power to reject the null [34]. To address this issue, a second set of studies have applied univariate unit root tests with structural breaks [35–45]. Most of these studies have found more evidence of stationarity [35–37,39–41,43–44], although some have reached mixed conclusions or failed to reject the unit root null [38,42,45].

To address the low power of conventional unit root tests to reject the unit root null in the presence of non-linearities, a third set of studies have applied non-linear unit root tests to energy consumption and production [33,37,38,46]. The overall findings from these studies is more consistent with energy consumption and production being non-stationary. A fourth set of studies has emphasised the low power of conventional unit root tests to reject the unit root null if the alternative is of a fractional form and have applied fractional integration unit root tests to energy consumption or production [47–52]. Overall, the results from these studies vary, depending on energy type and sector (see [15] for more details).

A final strand of the literature has applied panel tests with, and without, structural breaks, to address the short time span of data with univariate unit root tests [30–32,39,53–57]. The results from these studies are also mixed, although studies employing panel tests which accommodate structural breaks generally find more evidence of stationarity.

Many of these studies have employed aggregate energy consumption [30–33,36,37,39,41,43,53,57]. A problem with employing aggregate energy consumption is that some types of energy consumption might be more likely to be stationary than others [47,58]. In response to this issue, several of the recent studies have used disaggregated energy. However, most of the studies which have employed disaggregated energy have focused on specific fossil fuels [35,38,45–47,50,52,54–56,59]. There are few studies which have focused on renewable energy or its components and each of these studies is for the United States [42,49,51]. There are no such studies for other countries, which is a gap this study seeks to address.

3. Data

We collected annual data on total renewable electricity net generation (billion kW h) for 115 countries from the Energy Information Administration. This sample covers three countries in North America, 25 countries in Central & South America, 25 countries in Europe, four countries in the Middle East, 34 countries in Africa and 24 countries in Asia and Oceania. All data were transformed to natural logarithmic form prior to undertaking the analysis. The period studied spanned from 1980 to 2008. Table 1 reports the descriptive statistics that are based on the actual data. The largest mean is the United States (347.3696), while the smallest mean is Equatorial Guinea (0.0029). There is a large spread of production capacity between the largest and smallest countries. The highest standard deviation is China (128.2375), while the lowest standard deviation is Sao Tome and Principe (0.0014). Overall, 32 per cent of the countries in the sample have mean production of less than one billion kW h.

Table 2
Conventional panel unit root tests for full sample.

Test	Level	First difference
Levin, Lin and Chu	−9.3202***	−36.7985***
Im, Pesaran and Shin	−9.5118***	−43.6768***
Maddala and Wu—Fisher ADF	562.8860***	1837.7100***
Maddala and Wu—Fisher PP	648.1100***	5852.8300***

*** Indicates statistical significance at 1% level.

Table 3
Conventional panel unit root tests for regional panels.

Test	Level	First difference
North America		
Levin, Lin and Chu	−2.1259**	−7.5921**
Im, Pesaran and Shin	−2.5945***	−8.1259***
Maddala and Wu - Fisher ADF	17.1180***	53.3052***
Maddala and Wu—Fisher PP	19.5566***	68.0718***
Centre and South America		
Levin, Lin and Chu	−3.8908***	−19.9065***
Im, Pesaran and Shin	−3.3481	−20.2810***
Maddala and Wu—Fisher ADF	80.3314***	383.7010***
Maddala and Wu—Fisher PP	66.9445*	734.6760***
Europe		
Levin, Lin and Chu	−2.6599***	−15.4256***
Im, Pesaran and Shin	−1.8335**	−20.9971***
Maddala and Wu—Fisher ADF	104.8960***	406.8340***
Maddala and Wu—Fisher PP	108.5230***	1460.9500***
Middle East		
Levin, Lin and Chu	−1.3629*	−6.9384***
Im, Pesaran and Shin	−4.5803***	−8.7310***
Maddala and Wu—Fisher ADF	36.7630***	74.9094***
Maddala and Wu—Fisher PP	22.8561***	302.7990***
Africa		
Levin, Lin and Chu	−6.3740***	−21.1982***
Im, Pesaran and Shin	−6.9148***	−23.6894***
Maddala and Wu—Fisher ADF	215.1740***	534.3390***
Maddala and Wu—Fisher PP	325.4360***	1739.0800***
Asia and Oceania		
Levin, Lin and Chu	−4.6203***	−13.8763***
Im, Pesaran and Shin	−4.0622***	−18.5987***
Maddala and Wu—Fisher ADF	99.2536***	372.5900***
Maddala and Wu—Fisher PP	95.1819***	1318.9400***

*** Indicates statistical significance at 1% level, respectively.
** Indicates statistical significance at 5% level, respectively.
* Indicates statistical significance at 10% level, respectively.

4. Econometric methodology and results

We begin by applying four first generation panel unit root tests to renewable electricity generation for the 115 countries. The four panel unit root tests are proposed by Levin et al. [26], Maddala and Wu [27] and Im et al. [28]. Each has the null hypothesis that renewable electricity generation has a unit root. All four tests are well established in the literature so we do not provide details of

Table 4
Cross-section correlation and cross-section dependence test.

	Lag length (p)	1	2	3	4
Level	$\hat{\rho}$ bar	0.002	0.002	0.001	0.001
	CD	0.721	0.610	0.582	0.327
First difference	$\hat{\rho}$ bar	0.101	0.095	0.092	0.085
	CD	40.729***	38.463***	37.298***	34.369***

Notes: $\hat{\rho}$ bar denotes the simple average of the pairwise cross-section correlation coefficients from the ADF(p) regression. The critical values for CD statistics are 1.64, 1.96 and 2.57 at 10%, 5% and 1%, respectively.

*** Denotes statistical significance at the 1% level.

Table 5
Panel stationarity tests for full sample.

	Test statistics	Bootstrap critical values		
	Bartlett test	90%	95%	99%
No breaks (homogenous)	54.676***	10.894	15.036	25.319
No breaks (heterogeneous)	111.452***	14.697	19.644	27.722
Breaks (homogenous)	8.820	13.729	15.832	21.165
Breaks (heterogeneous)	25.411**	19.982	21.620	25.877
	Quadratic test			
No breaks (homogenous)	61.203***	10.748	14.654	21.800
No breaks (heterogeneous)	107.550***	13.680	17.457	26.870
Breaks (homogenous)	8.8763	13.729	15.959	20.160
Breaks (heterogeneous)	25.3147***	19.825	21.415	25.068

*** Denotes statistical significance at the 1% level.
** Denotes statistical significance at the 5% level.

the tests here (for a thorough review of these tests see, for example, [60]). The results of the four tests for the full sample are presented in Table 2. Each of the four tests suggest that renewable energy generation is stationary at the 1 per cent level. The results of the four tests for regional panels are presented in Table 3. The results generally suggest that renewable electricity generation is stationary for each of the regional panels. The possible exception is Central and South America, for which the Im et al. [28] test suggests renewable electricity generation contains a panel unit root and the Maddala and Wu [27] Fisher test only rejects the null hypothesis of a panel unit root at 10 per cent. Given Monte Carlo evidence that the Im et al. [28] and Maddala and Wu [27] tests outperform the Levin et al. [26] test [27,61], this result provides some support for the conclusion that renewable electricity generation in Central and South America contains a panel unit root, but overall the results strongly suggest that renewable electricity generation is stationary.

Before moving beyond the first generation tests, it is important to test for cross-sectional dependence. If there is cross-sectional dependence across countries, these four panel unit root tests will suffer from size distortions, which will bias the results [62]. To test for cross-sectional dependence we employ the cross-section dependence test statistic proposed by Pesaran [63] at lags 1–4. The null hypothesis for this test is cross-sectional independence. The results, which are reported in Table 4, fail to reject the null hypothesis, which implies that the results in Tables 2 and 3 are free from cross-sectional dependence.

The first generation tests have various limitations, which suggest that further investigation using a panel test that addresses the problems with these tests is warranted. One problem with each of these tests is that the null hypothesis is that they contain a panel unit root, while, in the case of renewable energy generation, it actually makes more sense to think of the null hypothesis as stationarity. This is because renewable energy generation has a long-run growth path consistent with stationarity and policies are being put in place to generate a permanent positive shock. A second problem is that none of the first generation tests allow for structural breaks, yet it is

Table 6
Panel stationarity tests for regional panels.

	Test statistics	Bootstrap critical values		
North America	Bartlett test	90%	95%	99%
No breaks (homogenous)	1.706	2.383	3.320	5.960
No breaks (heterogeneous)	3.161*	3.040	4.185	8.259
Breaks (homogenous)	0.588	4.558	6.041	9.136
Breaks (heterogeneous)	1.053	6.181	8.640	16.144
	Quadratic test			
No breaks (homogenous)	1.864	2.373	3.290	5.423
No breaks (heterogeneous)	3.227*	3.043	5.700	7.591
Breaks (homogenous)	0.786	4.404	5.885	9.180
Breaks (heterogeneous)	1.143	6.335	8.356	14.237
Central & South America				
No breaks (homogenous)	32.323***	6.686	8.810	14.224
No breaks (heterogeneous)	47.809***	7.081	9.953	15.278
Breaks (homogenous)	2.610	7.848	9.225	11.859
Breaks (heterogeneous)	9.892	10.179	11.672	14.926
	Quadratic test			
No breaks (homogenous)	31.950***	5.964	8.423	13.805
No breaks (heterogeneous)	44.683***	6.862	9.344	16.457
Breaks (homogenous)	2.373	7.879	9.021	12.315
Breaks (heterogeneous)	9.735	10.282	11.709	14.756
Europe				
No breaks (homogenous)	18.816***	6.557	9.153	15.074
No breaks (heterogeneous)	70.793***	7.370	9.670	14.304
Breaks (homogenous)	2.192	5.965	7.285	10.688
Breaks (heterogeneous)	11.173	11.866	13.692	17.685
	Quadratic test			
No breaks (homogenous)	25.844***	6.369	8.304	13.974
No breaks (heterogeneous)	70.347***	6.591	8.576	13.488
Breaks (homogenous)	2.352	5.295	6.776	10.228
Breaks (heterogeneous)	11.178	11.607	13.393	16.667
Middle East				
No breaks (homogenous)	7.177***	2.429	3.384	5.734
No breaks (heterogeneous)	11.377***	3.118	4.369	7.333
Breaks (homogenous)	1.434	3.561	4.579	6.752
Breaks (heterogeneous)	1.906	4.028	5.226	10.124
	Quadratic test			
No breaks (homogenous)	6.457***	2.536	3.619	5.693
No breaks (heterogeneous)	11.206***	3.268	4.640	7.416
Breaks (homogenous)	1.340	3.324	4.348	6.441
Breaks (heterogeneous)	1.895	3.651	4.779	8.329
Africa				
No breaks (homogenous)	30.734***	5.223	7.226	10.663
No breaks (heterogeneous)	58.155***	7.380	9.824	15.665
Breaks (homogenous)	5.551	10.069	12.261	18.385
Breaks (heterogeneous)	15.001**	12.154	13.568	16.272
	Quadratic test			
No breaks (homogenous)	31.839***	5.305	7.134	11.624
No breaks (heterogeneous)	56.150***	7.379	9.964	17.303
Breaks (homogenous)	5.591	10.002	11.722	16.280
Breaks (heterogeneous)	14.883**	12.048	13.600	16.908
Asia & Oceania				
No breaks (homogenous)	30.501***	6.345	9.292	16.565
No breaks (heterogeneous)	48.797***	7.299	9.834	17.234
Breaks (homogenous)	9.975**	8.104	9.226	12.456
Breaks (heterogeneous)	20.513**	15.520	17.718	22.891
	Quadratic test			
No Breaks (Homogenous)	30.395***	6.539	9.699	16.250
No Breaks (Heterogeneous)	46.298***	7.405	9.806	17.685
Breaks (Homogenous)	10.204**	8.071	9.247	11.949
Breaks (Heterogeneous)	20.608**	15.326	17.424	21.650

*** Indicates statistical significance at 1% level, respectively.
** Indicates statistical significance at 5% level, respectively.
* Indicates statistical significance at 10% level, respectively.

Table 7
Stationarity tests for individual countries.

Country	*t*-Statistic	TB1	TB2	10%	5%	1%
Afghanistan	0.0578	1991	2001	0.1000	0.1220	0.1750
Albania	0.0661	1994	2006	0.0940	0.1160	0.1690
Algeria	0.1708**	1995	2002	0.0990	0.1230	0.1760
Angola	0.1120*	1991	2003	0.0980	0.1220	0.1780
Argentina	0.0524	1992	2000	0.1010	0.1250	0.1820
Australia	1.5723***	1990	1998	0.1020	0.1250	0.1860
Austria	0.0564	1987	1997	0.1040	0.1290	0.1850
Bangladesh	0.4737***	1988	2001	0.0990	0.1240	0.1790
Belgium	0.0558	1986	2000	0.1020	0.1250	0.1850
Bhutan	0.3850***	1985	2005	0.0960	0.1180	0.1730
Bolivia	0.3154***	1990	1998	0.1030	0.1260	0.1870
Brazil	0.1054*	1984	1995	0.1050	0.1290	0.1870
Bulgaria	0.0337	1984	2002	0.0980	0.1220	0.1780
Burundi	0.7413***	1982	1986	0.1130	0.1400	0.2090
Caledonia	0.2900***	1987	1990	0.1090	0.1360	0.2040
Cambodia	0.0441	1988	1997	0.1040	0.1290	0.1870
Cameroon	0.2055***	1984	1996	0.1040	0.1280	0.1870
Canada	0.1852**	1983	1993	0.1080	0.1350	0.1930
Central African Republic	0.1895***	1985	2004	0.0970	0.1200	0.1760
Chile	0.1528**	1991	2000	0.1010	0.1240	0.1800
China	0.1148*	1992	2000	0.1000	0.1240	0.1820
Colombia	0.3734***	1983	1993	0.1090	0.1340	0.1950
Congo	0.2926***	1984	2003	0.0990	0.1210	0.1780
Costa Rica	0.1249*	1990	1998	0.1020	0.1270	0.1860
Cuba	0.0894	1992	2005	0.0970	0.1200	0.1790
Denmark	0.1119*	1987	1996	0.1050	0.1290	0.1870
Dominica	0.2112***	1982	1997	0.1030	0.1280	0.1860
Dominican Republic	0.0753	1988	2002	0.1000	0.1230	0.1810
Ecuador	0.3785***	1983	1995	0.1050	0.1300	0.1890
Egypt	0.0630	1992	1998	0.1030	0.1260	0.1860
El Salvador	0.0806	1994	2004	0.0970	0.1200	0.1750
Equatorial Guinea	0.1367**	2001	2006	0.0960	0.1190	0.1680
Ethiopia	0.0952	1987	2000	0.1010	0.1250	0.1840
Faroe Islands	0.0800	1987	2001	0.0990	0.1240	0.1810
Finland	0.1000	1991	1997	0.1040	0.1290	0.1950
France	0.0575	1988	1991	0.1090	0.1350	0.1990
Gabon	0.4689***	1981	1993	0.1080	0.1340	0.1960
Germany	0.2116***	1999	2005	0.0970	0.1200	0.1770
Ghana	0.1146	1982	1985	0.1150	0.1450	0.2070
Greece	0.1482**	1994	2002	0.0990	0.1210	0.1780
Guatemala	0.4258***	1985	2002	0.0990	0.1230	0.1810
Haiti	0.1181**	1992	2006	0.0960	0.1180	0.1750
Honduras	0.8242***	1985	1987	0.1130	0.1410	0.2030
Hungary	0.2879***	1989	2003	0.0980	0.1210	0.1780
Iceland	0.4193***	1997	2006	0.0960	0.1180	0.1740
India	0.1917***	1989	2004	0.0960	0.1180	0.1790
Indonesia	0.1314**	1985	1997	0.1020	0.1260	0.1830
Iran	0.1199*	1998	2001	0.1000	0.1220	0.1820
Iraq	0.5241***	1989	1991	0.1090	0.1330	0.1970
Ireland	0.3110***	1997	2004	0.0970	0.1180	0.1720
Italy	0.0789	1988	1990	0.1100	0.1370	0.1980
Cote dIvoire (IvoryCoast)	1.0354***	1982	1994	0.1060	0.1310	0.1940
Jamaica	0.1631**	1986	2003	0.0970	0.1220	0.1770
Japan	0.2031***	1987	1996	0.1050	0.1290	0.1910
Kenya	0.0844	1987	2001	0.0980	0.1220	0.1790
Korea, North	0.0430	1985	1995	0.1060	0.1310	0.1910
Korea, South	0.5164***	1984	1997	0.1040	0.1280	0.1870
Laos	0.1397**	1995	1998	0.1040	0.1300	0.1900
Lebanon	0.1722**	2002	2005	0.0970	0.1190	0.1790
Luxembourg	0.8493***	1997	2003	0.0970	0.1210	0.1750
Madagascar	0.1351**	1981	1995	0.1050	0.1290	0.1870
Malawi	0.1951***	1989	1999	0.1010	0.1250	0.1830
Malaysia	0.1910***	1983	1998	0.1030	0.1260	0.1860
Mali	0.6838***	1982	1991	0.1080	0.1330	0.1940
Mauritania	0.0619	1985	2002	0.0980	0.1210	0.1780
Mauritius	0.3113***	1984	1989	0.1120	0.1370	0.2040
Mexico	0.1287**	1988	2004	0.0950	0.1190	0.1730
Morocco	0.1494**	1981	1986	0.1140	0.1410	0.2060
Mozambique	0.1575**	1983	1998	0.1030	0.1280	0.1870
Burma (Myanmar)	0.1921***	1990	2001	0.1000	0.1230	0.1830
Nepal	0.1598**	1986	1999	0.1010	0.1260	0.1870
Netherlands	0.1124*	1986	1995	0.1050	0.1300	0.1930
Nicaragua	0.0520	1984	2004	0.0970	0.1200	0.1750
Nigeria	0.1213*	1985	1990	0.1110	0.1370	0.1970
Norway	1.0041***	1987	2004	0.0970	0.1200	0.1760

Table 7 (*continued*)

Country	*t*-Statistic	TB1	TB2	10%	5%	1%
New Zealand	0.1764**	1985	1992	0.1090	0.1350	0.2010
Pakistan	0.1256**	1986	2002	0.0990	0.1210	0.1790
Panama	0.7246***	1984	1998	0.1020	0.1270	0.1870
Paraguay	0.2888***	1984	1988	0.1130	0.1400	0.2050
Peru	0.2161***	1985	1999	0.1020	0.1250	0.1820
Philippines	0.5391***	1983	1998	0.1040	0.1280	0.1890
Papua New Guinea	0.1207*	1982	1994	0.1060	0.1310	0.1900
Poland	0.1523**	1996	2004	0.0970	0.1200	0.1720
Portugal	0.3867***	1982	1995	0.1050	0.1300	0.1880
Puerto Rico	0.2023***	1984	1989	0.1110	0.1370	0.2020
Reunion	0.2629***	1984	1996	0.1030	0.1290	0.1870
Romania	0.0662	1987	1994	0.1070	0.1310	0.1920
Rwanda	0.3383***	1999	2005	0.0970	0.1200	0.1740
Saint Vincent/Grenadines	0.2154***	1984	1989	0.1120	0.1400	0.2040
Samoa	0.6431***	1983	1996	0.1040	0.1290	0.1900
Sao Tome and Principe	0.6354***	2000	2005	0.0980	0.1200	0.1720
South Africa	0.1463**	1991	1995	0.1060	0.1310	0.1970
Spain	0.0883	1995	2002	0.0990	0.1210	0.1730
Sri Lanka	0.0417	1983	1989	0.1110	0.1370	0.2000
Sudan	0.1252*	1984	1998	0.1030	0.1270	0.1850
Suriname	0.0578	1988	1999	0.1010	0.1250	0.1810
Swaziland	0.2019***	1984	2002	0.0980	0.1210	0.1760
Sweden	0.3703***	1982	1996	0.1040	0.1280	0.1910
Switzerland	0.2203***	1998	2001	0.1000	0.1240	0.1800
Syria	0.1828**	1989	1999	0.1020	0.1270	0.1870
Taiwan	0.2006***	1996	2004	0.0960	0.1190	0.1710
Tanzania	0.5377***	1988	1997	0.1030	0.1280	0.1870
Thailand	0.0978	1981	1994	0.1070	0.1320	0.1910
Togo	0.1180*	1988	1999	0.1020	0.1260	0.1880
Trinidad and Tobago	0.0726	1985	2006	0.0950	0.1170	0.1710
Tunisia	0.0674	1983	2002	0.0990	0.1230	0.1810
Turkey	0.6260***	1986	1992	0.1080	0.1330	0.1960
Uganda	0.1907***	1991	1999	0.1020	0.1240	0.1840
United Kingdom	0.1090*	1986	2000	0.1010	0.1250	0.1860
Uruguay	0.0738	1982	2003	0.0980	0.1220	0.1810
United States	0.0376	1986	1988	0.1110	0.1390	0.2000
Venezuela	0.1041	1986	1993	0.1070	0.1340	0.1920
Vietnam	0.1364**	1988	1994	0.1050	0.1290	0.1900
Zambia	0.1385**	1986	2004	0.0970	0.1210	0.1760
Zimbabwe	0.2182***	1992	1998	0.1030	0.1270	0.1840

*** Denotes statistical significance at the 1% level.
** Denotes statistical significance at the 5% level.
* Denotes statistical significance at the 10% level.

reasonable to expect that renewable energy production has been the subject of multiple structural breaks over the last three decades. The Carrioni-i-Silvestre et al. [29] test addresses both of these limitations. Specifically, it treats panel stationarity as the null hypothesis and it accommodates multiple structural breaks at the level of individual countries.

The Carrioni-i-Silvestre et al. [29] test generalizes the Hadri [64] panel stationarity test to allow for multiple structural breaks. The Hadri [64] test, in turn, is a panel version of the univariate Kwiatowski et al. [65] univariate stationarity test. The Carrioni-i-Silvestre et al. [29] test statistic is the average of the Kwiatowski et al. [65] test statistic across countries. The dates of the structural breaks are determined using the method proposed by Bai and Perron [66] (for further details see [29]). Table 5 presents the results of the Hadri [64] panel stationarity test, as well as the Carrioni-i-Silvestre et al. [29] test for the full sample of 115 countries. We report both Bartlett and Quadratic tests under the alternative assumptions that the long run variance is homogenous and heterogeneous. We bootstrap the critical values based on 2000 replications, which addresses all forms of cross-sectional dependence. The results of the Hadri [64] test reject the null hypothesis of panel stationarity. The Carrioni-i-Silvestre et al. [29] test with multiple structural breaks fails to reject the null of panel stationarity when the long-run variance is assumed to be homogenous, but rejects the null hypothesis of stationarity with heterogeneous long-run variance. Since the assumption that the long-run variance is heterogeneous makes more sense for renewable electricity generation across 115 countries, the results are more consistent with the existence of a panel unit root in renewable electricity generation. Overall, this result for the Hadri [64] and Carrioni-i-Silvestre et al. [29] tests differ from the findings of the first generation panel unit root tests and points to the relevance of treating the null hypothesis as being panel stationarity.

Table 6 presents the results of the Hadri [64] and Carrioni-i-Silvestre et al. [29] tests for the regional panels. Overall, while the results are mixed, findings for two-thirds of the region are consistent with stationarity. For North America, both tests suggest that renewable electricity generation is stationary, while for Asia and Oceania and Africa, both tests suggest renewable electricity generation contain a panel unit root. For Central and South America, Europe and the Middle East, findings from the two tests diverge—the Hadri [64] test suggests that renewable electricity generation contains a panel unit root, while the Carrioni-i-Silvestre et al. [29] test suggests that renewable electricity generation is stationary. The results for Central and South America, Europe and the Middle East are consistent with previous studies in the energy literature which have found that the Carrion-i-Silvestre et al. [29] test overturns the Hadri [64] finding of a panel unit root because it takes account of structural breaks

in the data (see e.g., [30]). Where the findings diverge, the results for the Carrion-i-Silvestre et al. [29] test are more reliable because failure to include structural breaks introduces size distortions and biases the Hadri [64] test toward rejecting the null of panel stationarity.

Table 7 presents the results for the Carrioni-i-Silvestre et al. [29] test, allowing for two heterogeneous structural breaks in renewable electricity generation for each of the 115 countries in the sample. The results are generally consistent with the results of the panel test for the full sample reported in Table 5. Specifically, we reject the null hypothesis of panel stationarity for 84 countries, or 73 per cent of the total, at 10 per cent or better. Narayan et al. [54] speculated that energy production is more likely to be non-stationary in countries in which production exhibits high volatility, reflected in a high standard deviation. However, there seems to be little relationship between volatility in production and order of integration in our sample. Of the 25 per cent of countries with least volatility in renewable electricity generation, for just 5 per cent of the total sample was renewable electricity generation a stationary process. This finding is consistent with the results reported in Narayan et al. [54] and Barros et al. [52]. Maslyuk and Smyth [46] suggested that energy production is more likely to contain a unit root in countries which are large producers because in such countries shocks will result in larger deviations from the long-run growth path. There is little support for this suggestion in our findings. For the 25 per cent of countries with the lowest mean in renewable electricity generation, for just 10 per cent of the total sample is renewable electricity generation stationary. Thus, the order of integration of renewable electricity generations seems largely unrelated to either the size of production or volatility in production.

The location of the break dates vary considerably across the countries in the sample. Many are tied to specific policies and events in particular countries. Several of the breakpoints in the high income countries coincided with the oil price spikes at the beginning of the 1980s and in the late 1980s and early 1990s which were catalysts for increased expenditure on research and development in these countries [24]. Other break dates are linked with the ratification of international treaties, such as the Kyoto Protocol, which were catalysts for finding alternatives to fossil fuels. In Europe some breaks in the mid-to-late 1980s are linked to the Chernobyl disaster. Some European countries experienced elevated radiation levels which were responsible for policy makers substituting renewable energy for nuclear energy [67]. Other break dates in Europe are linked to specific measures implemented to increase the share of renewable energy from the mid-to-late 1990s. These measures include a European Commission White Paper, published in 1997, that set the first targets for increased renewable energy use in the overall energy mix [68] and later directives – the renewable electricity Directive 2001/77/EC and biofuels Directive 2003/30/EC – which set targets for the share of renewable energy in the electricity and transport sectors by 2010 [7].

5. Conclusion

There is much debate about the effectiveness of policies designed to increase the share of renewable energy in the energy mix. An important component of this debate is whether it is feasible to increase the generation of renewable energy for electricity and how best to do this. For example, increasing the share of renewable energy for electricity are key components of the renewable energy platform in both the European Union and the United States. This paper has considered the likely effectiveness of policies designed to increase the share of renewable electricity generation through examining the order of integration of renewable electricity generation time series data. The results from the first generation panel unit root tests generally suggest that renewable electricity generation is stationary, but when we treat the null hypothesis as stationarity and allow for structural breaks, we find much more support for the existence of a unit root in renewable electricity generation. While the results for the regional panels vary across regions, for the panel for the full sample and for almost three quarters of the sample we find that renewable electricity generation contains a unit root. Although one needs to be careful when drawing conclusions for individual countries and regions, overall this result suggests that shocks to renewable electricity generation will result in a permanent deviation from the long-run growth path. For the full panel, this suggests that policies designed to have a permanent positive impact on renewable electricity generation that generate continuing annual shocks are likely to be successful, rather than policies which result in one-time shocks, such as investment incentives or tax credits.

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